Final report on grant NNX12AH44G

Title: Investigating global ion and neutral atom populations with IBEX and Voyager

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Personnel

This grant supported salary for V. Florinski, J. Heerikhuisen, F. Alouani Bibi, X. Guo, and G. P. Zank.

Research activity report

The main objective of this project was to investigate pickup ion (PUI) production in the solar wind and heliosheath (the region between the termination shock and the heliopause) and compute the distributed energetic neutral atom fluxes throughout the helioshpere. The simulations were constrained by comparing the model output against observations from Ulysses, New Horizons, Voyager 1 and 2, and IBEX space probes. As evidenced by the number of peer reviewed journal publications resulting from the project (13 plus three submitted) and their citation rate (156 citations over three years), the project has made a lasting contribution to the field. The outcome is a significant improvement of our understanding of the pickup ion production and distribution in the distant heliosphere.

The team has accomplished the entire set of tasks A-H set forth in the proposal. Namely, the transport modeling framework has been augmented with two populations of pickup ions (PUIs), the boundary conditions for the plasma and interstellar neutral hydrogen were verified against Ulysses and New Horizons PUI and an optimal set of velocity diffusion parameters established. The multi-component fluxes of PUIs were computed and isotropic velocity distributions generated for each cell in the computer simulation that covered the heliosphere from 1.5 AU to the heliopause. The distributions were carefully compared with in situ measurements at 3 AU

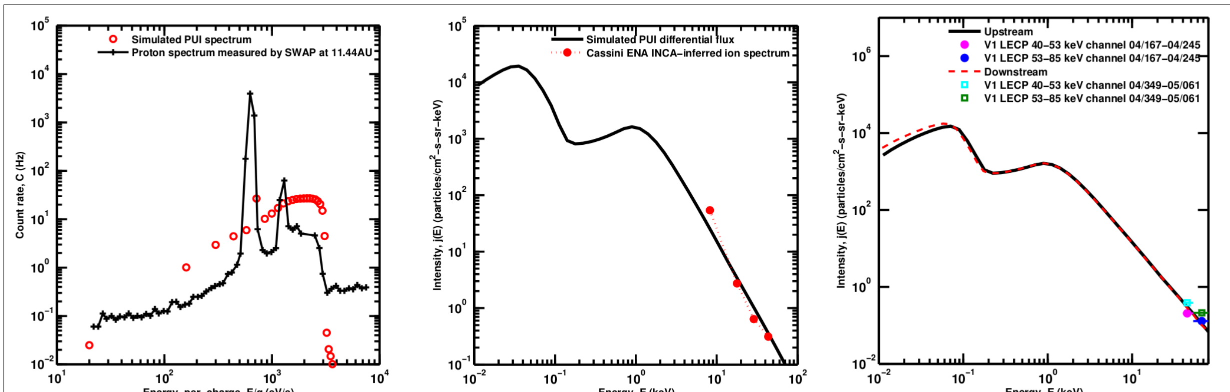

Figure 1. Model-derived PUI velocity distributions at 12 AU (left) and 80-90 AU (center and right). The symbols show spacecraft data for comparison.

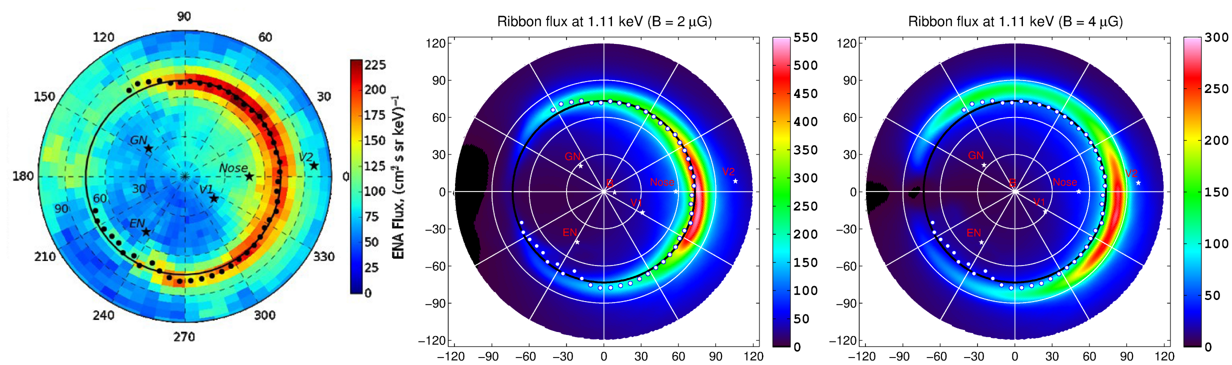

Figure 2. IBEX ENA data at 1.1 keV (left) plotted to highlight the circularity of the ribbon. Middle and right show results from simulations with interstellar magnetic field strengths of 0.2 nT and 0.4 nT, respectively. The geometry of the observed ribbon appears to rule out LISM magnetic field strengths above 3mG.

(Ulysses), 12 AU (New Horizons), and 80-90 AU (Voyager 1 and 2) as well as those inferred from ENA fluxes measured by Cassini and IBEX (Wu et al., 2016). Some examples of model-data comparison are shown in Figure 1.

We have used coupled MHD-plasma and kinetic-neutral code to investigate the likely range of plasma and magnetic field parameters in the local interstellar medium (LISM), based on the assumption that the shape of the IBEX ribbon could be used to determine the orientation of the interstellar magnetic field. While the magnetic field is believed to be oriented toward the center of the ribbon, constraining its strength requires comparing the model-predicted angular diameter and circularity of the ribbon with the observations. The study, published in Heerikhuisen et al. (2014), found that the most likely range for the LISM magnetic field strength is between 0.2 and 0.3 nT, which is less than previously thought. Figure 2 shows the IBEX data (left) and compares it to the simulation with a 0.2 nT interstellar magnetic field (center) and a 0.4 nT (right).

We have also investigated the morphology of the heliopause transition region encountered by Voyager 1 in 2012 and the unexpected “pancake” anisotropies of PUIs measured near the so-called heliocliff structure, the point of a rapid drop in heliospheric energetic particle intensities

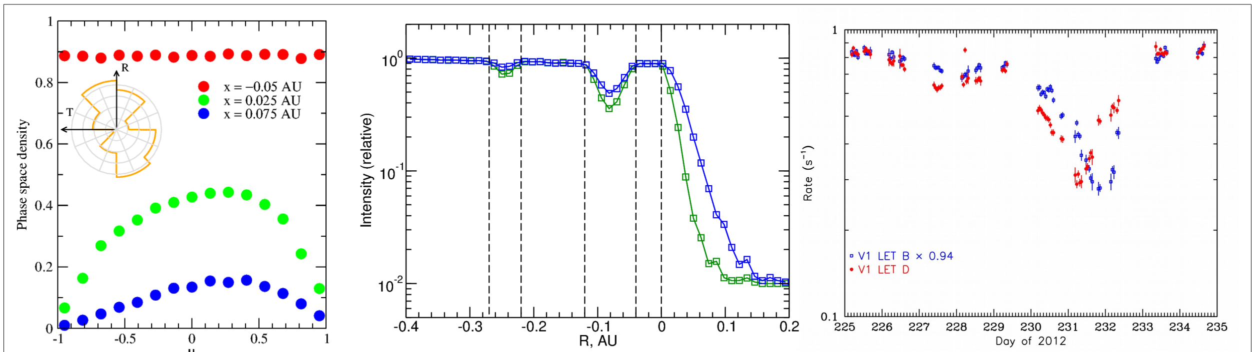

Figure 3. Left: pitch-angle distributions of 5 MeV pickup protons before the heliocliff (red) and after (green and blue). Center: simulated intensity variations of 5 MeV pickup protons at zero degree (green) and 90 degree (blue) pitch angles in the heliopause transition region. Right: measured intensities of 2-8 MeV protons around the time of the crossing of the second flux tube.

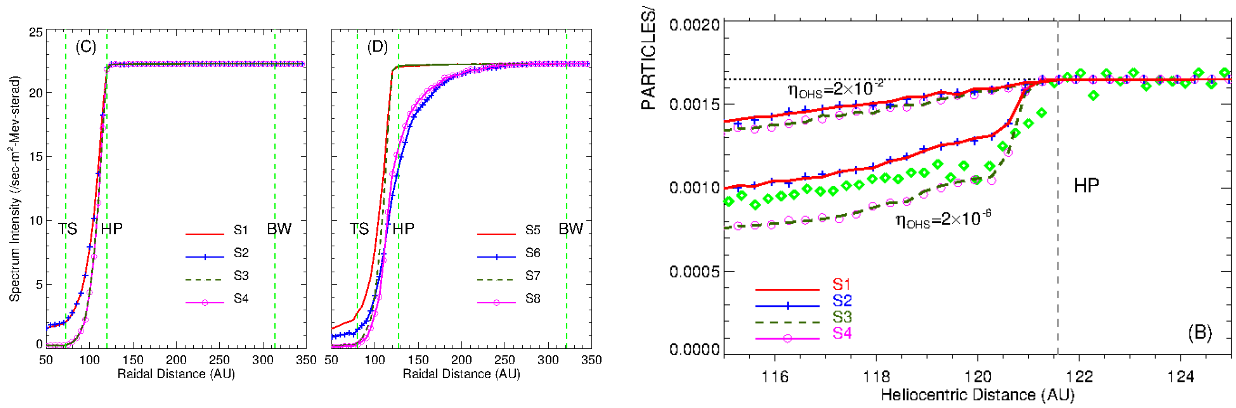

Figure 4. Left: simulated intensities of 100 MeV galactic cosmic ray protons in the Voyager 1 direction for several possible diffusion scenarios. Right: intensities of 180 MeV/n ions observed near the heliopause by Voyager 1 (symbols) compared with the simulation results.

and an increase in magnetic field strength (Florinski et al., 2013). We have shown that the transition region was permeated by alternating magnetic flux tubes from the heliosheath and interstellar side. This structure resulted from a pressure-driven interchange instability operating at the heliopause as a consequence of an outward curvature of magnetic field lines and an inward plasma pressure gradient (Florinski, 2015). The hypothesis naturally explained the alignment of the field at the boundaries of the flux tubes and at the heliocliff itself. We then looked more closely at the crossing of the flux tubes by Voyager 1 and discovered the time shift between two opposing cosmic-ray telescopes as a result of circulating anisotropy from the gradient of the density of the ions' guiding centers (Florinski et al., 2015). This measurement allowed us to infer the plasma radial velocity, which Voyager 1 could not measure directly (the velocity turned out to be close to zero and toward the Sun). Figure 3 shows the computed pitch-angle distribution function and the simulated and measured intensity variation across one of the flux tubes demonstrating the time delay.

Next, the team has studied the modulation of galactic cosmic rays in the inner and outer heliosheaths using three-dimensional numerical simulations. Our models predicted a negligible amount of modulation in the outer heliosheath because of weak scattering of cosmic ray ions owing to very low levels of magnetic fluctuation power at wave numbers relevant to the transport of cosmic rays with MeV to GeV energies. Figure 4 shows the 100 MeV/n galactic cosmic ray intensity along Voyager 1 direction. Our results contradict the previous results from the two cosmic ray research groups from Germany and South Africa, but corroborate the theoretical predictions from the research group in University of Arizona. Voyager observation show no measurable long-term modulation during the 3.5 years in the outer heliosheath, which agrees with our model (Guo and Florinski, 2015). We were able to reproduce one of the large step increases measured by Voyager 1 just prior to its heliocliff encounter (Figure 4, right).

We have also worked on including a solar cycle into the simulation of energetic neutral atoms (ENAs), and also a separate investigation into how the use of a kappa distribution in the heliosheath should be combined with a careful treatment of the charge-exchange cross-section. We employed a simplified solar cycle where the solar wind source is divided into two regions – one with slow solar wind near the equator and fast solar wind over the poles. The transition between the two regions occurs at a fixed latitude that varies sinusoidally over the 11 year solar cycle. At the same time the magnetic dipole axis is tilted from upright (aligned with the solar rotation axis)

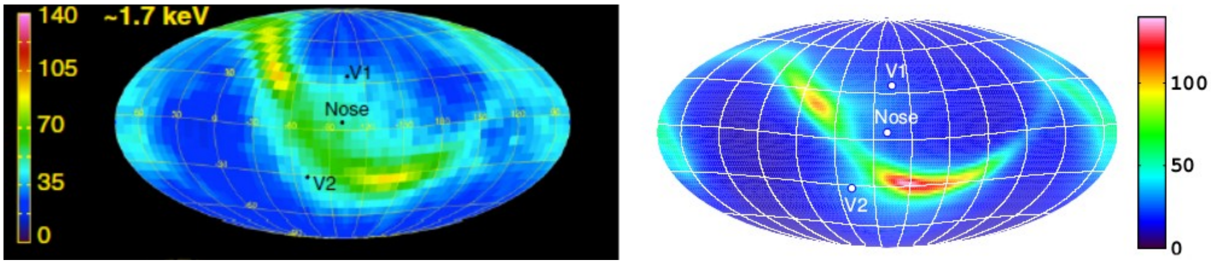

Figure 5. Left: average energetic neutral atom flux at 1.7 keV for the first 5 years of the IBEX mission. Right: corresponding simulated flux.

at solar minimum to laying in the equatorial plane at solar maximum. Our post-processing analysis of the ENAs was modified to operate in a time-varying way, so that the ENA propagation time from the inner and outer heliosheaths was correctly accounted for. Figure 5 shows a comparison of the ENA flux observed by IBEX-Hi's passband 4 (centered on 1.7 keV) over the first 5 years of operations (left) along with flux from the simulation for the corresponding energy range and time frame. The time-averaged flux levels and relative distributions around the ribbon are remarkably similar (Zirnstein et al., 2015).

Partially funded by this grant was the first ever in situ measurement of the magnetic turbulence spectrum in the region outside the heliosphere (i.e., in interstellar space) by Voyager 1. This was done by analyzing Voyager magnetometer data over a 486 day interval in 2013-2014 free from shocks and other transient structures. The power spectrum of the fluctuations had a slope close to the Kolmogorov power law of -5/3, and its intensity in the interval of wave numbers covered by the data sample was consistent with interstellar spectrum extending from 20 parsec over more than 12 decades in wave numbers down to sub-AU scales. This observation supported our various models that assumed nearly scatter-free propagation of charged particles along magnetic field lines. Figure 6 shows the measured power spectrum (left) and the possible interpretation as portion of the interstellar spectrum inferred from remote astrophysical observations (Burlaga et al., 2015).

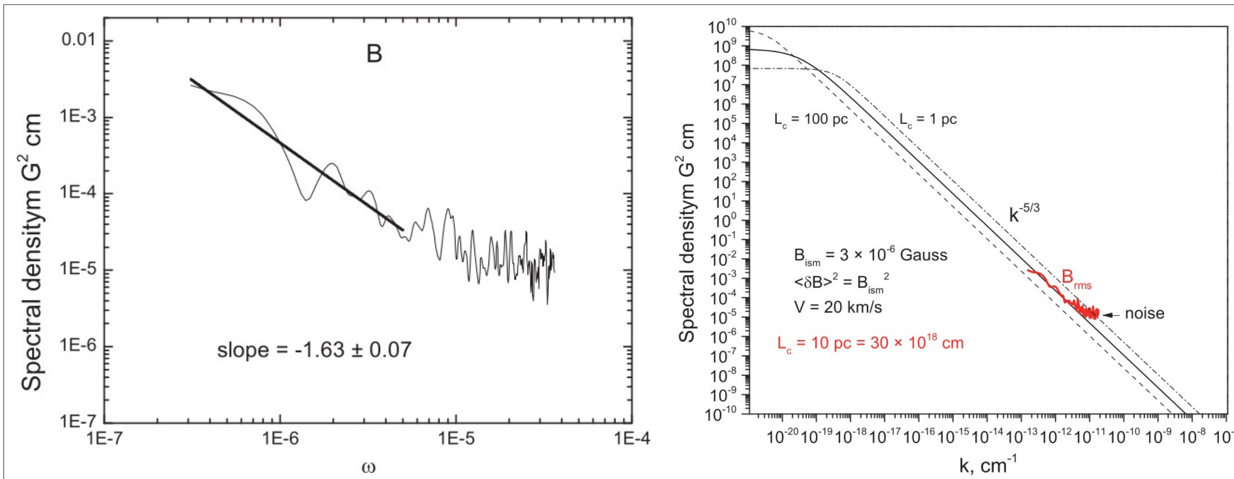

Figure 6. Left: Frequency spectrum of the magnitude of B during a 468 day interval and a power-law fit at low frequencies (the highest frequency data are dominated by the instrument noise producing the apparent hardening of the spectrum). Right: a comparison between the in situ spectrum (red) and a Kolmogorov power law inferred from remote sensing.

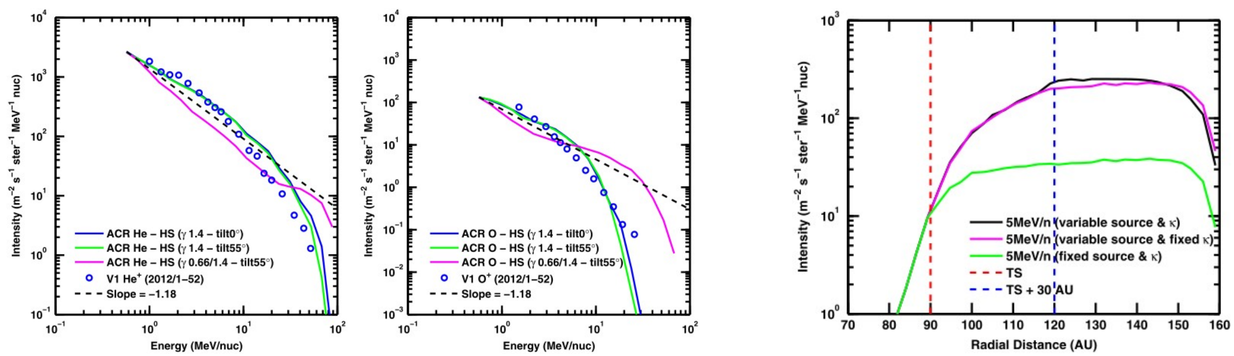

Figure 7. The left two panels show simulated spectra of anomalous helium and oxygen in the heliosheath and compares them with the spectra measured by Voyager 1 in early 2012 (blue circles). The right panel shows the simulated radial dependence of 5 MeV/n anomalous He along Voyager 1 trajectory that takes into account source strength and diffusion changes with the solar cycle.

Another investigation involved a careful analysis of the charge-exchange process between a neutral hydrogen atom and a collection of protons that follow a kappa-distribution. Kappa-distributions are often used in modeling to allow for the presence of high energy tails in the velocity distribution, and in our modeling these tails represent the presence of pick-up ions. In this work we showed that the traditional assumption that the charge-exchange cross-section is approximately the same for the range of protons charge-exchange partners in the distribution is only valid for a Maxwellian, while for a Kappa-distribution the energy dependence of the cross-section needs to be taken into account to avoid an excessive number of collisions with high energy protons (Heerikhuisen et al., 2015).

In a series of two papers, we have investigated the micro-physics of space where the IBEX ribbon emission originates and provided an explanation of its properties. The difficulty with the leading explanation of the ribbon as originating from secondary pickup ions in a ring distribution charge-exchanging on interstellar neutral hydrogen is the kinetic instabilities of such distributions. We performed a thorough modeling analysis of the instability for a range of possible ring topologies, including those derived from global Monte-Carlo simulations of interstellar hydrogen in the heliosphere. We have discovered the “stability gap” in ring temperature space and identified the range of stable distributions for the plasma conditions in the outer heliosheath (Florinski et al., 2016; Niemiec et al., 2016).

Educational activity summary

The grant partially supported a graduate student in the Space Science Department, Shirley Wu. Under the guidance of PI Florinski, the student has developed a computer model of PUI transport in the heliosphere that includes the transport mechanisms (ionization, convection, cooling and acceleration, and momentum diffusion) relevant to the formation of PUI core and suprathermal tails. This model has been integrated into the overall UAH modeling framework for heliospheric plasmas. The results shown in Figure 1 represent her research. Wu has submitted a first-authored manuscript to the Astrophysical Journal and published a proceedings paper in 2015. She presented here results at the Annual International Astrophysics Conferences in Myrtle Beach (2014) and Tampa (2015) as well as at the Fall AGU meeting in San Francisco (2014). Wu is on track to defend her Ph. D. dissertation in Summer of 2016.

The grant also partially supported the joint work of PI Florinski and another graduate student, Udara Senanayake, who graduated from the UAH in 2015 with a Ph. D. in Physics. Udara has developed a model of anomalous cosmic ray (ACR) acceleration and transport in the vicinity of the termination shock. His first paper (Senanayake and Florinski, 2013) explored the influence of the global shape of the shock (curvature and bluntness) on the efficiency and the preferred sites of ACR acceleration. He found that the the highest-energy helium ACRs are more likely to be accelerated on the tailward part of the termination shock which would explain the positive radial gradient of ACRs observed by Voyager 1 in the heliosheath. Following up on this paper, he published another (Senanayake et al., 2015), where he studied the solar cycle effects on the acceleration of helium and oxygen ACRs. He proposed that the changing solar-wind conditions cause the unrolling of the spectra in the heliosheath. He has shown that the spectral evolution of ACRs in the heliosheath at Voyager 1 could be explained by an increase in the source strength and an enhancement in diffusion as a result of a decrease of the turbulent correlation length in the declining phase of the solar cycle. Figure 7 compares He and O ion spectra computed for different values of the current sheet tilt angle with Voyager 1 observations.

Published journal papers supported by the grant

1. Florinski, V., Guo, X., Balsara, D. S., and Meyer, C., MHD modeling of solar system processes on geodesic grids, Astrophysical Journal Supplement Series, 205, 19 (2013).

2. Zank, G. P., Heerikhuisen, J., Wood, B. E., Pogorelov, N. V., Zirnstein, E., and McComas, D. J., Heliospheric structure: the bow wave and the hydrogen wall”, Astrophysical Journal, 763, 20 (2013).

3. Florinski, V., Jokipii, J. R., le Roux, J. A., and Aloiani-Bibi, F., Energetic particle anisotropies at the heliospheric boundary, Astrophysical Journal Letters, 776, L37 (2013).

4. Senanayake, U., and Florinski, V., Is the acceleration of anonymous cosmic rays affected by the geometry of the termination shock? Astrophysical Journal, 778, 122 (2013).

5. Heerikhuisen, J., Zirnstein, E. J., Funsten, H. O., Pogorelov, N. V., and Zank, G. P., The effect of new interstellar parameters on the heliosphere and ENAs from the interstellar boundary, Astrophysical Journal, 784, 73 (2014).

6. Guo, X., and Florinski, V., Galactic cosmic-ray modulation near the heliopause, Astrophysical Journal, 793, 18 (2014).

7. Guo, X., and Florinski, V., Corotating interaction regions and the 27-day variation of galactic cosmic rays intensity at 1 AU during the cycle 23/24 solar minimum, Journal of Geophysical Research, 119, 2411 (2014).

8. Florinski, V., Stone, E. C., Cummings, A. C., and le Roux, J. A., Energetic particle anisotropies at the heliospheric boundary. II. Transient features and rigidity dependence, Astrophysical Journal, 803, 47 (2015).

9. Senanayake, U., Florinski, V., Cummings, A. C., and Stone, E. C., Spectral evolution of anomalous cosmic rays at Voyager 1 beyond the termination shock, Astrophysical Journal, 804, 12 (2015).

10. Zirnstein, E. J., Heerikhuisen, J., Pogorelov, N. V., McComas, D.J., and Dayeh, M. A., Simulations of a dynamic solar cycle and its effects on the Interstellar Boundary Explorer ribbon and globally-distributed energetic neutral atom flux, Astrophysical Journal, 804, 5

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11. Heerikhuisen, J., Zirnstein, E. J., and Pogorelov, N.V., Kappa-distributed protons in the solar wind and their charge-exchange coupling to energetic hydrogen, Journal of Geophysical Research, 120, 1516 (2015).
12. Burlaga, L. F., Florinski, V., and Ness, N. F., In situ observations of magnetic turbulence in the local interstellar medium, Astrophysical Journal Letters, 804, L31 (2015).
13. Florinski, V., Magnetic flux tube interchange at the heliopause, Astrophysical Journal, 813, 49 (2015).

Submitted journal papers supported by the grant

1. Florinski, V., Heerikhuisen, J., Niemiec, J., and Ernst, A., The IBEX ribbon and the pickup ion ring stability in the outer heliosheath I. Theory and hybrid simulations, Astrophysical Journal, submitted (2016).
2. Niemiec, J., Florinski. V., Heerikhuisen. J., and Nishikawa, K.-I., The IBEX ribbon and the pickup ion ring stability in the outer heliosheath II. Monte-Carlo and PIC model results, Astrophysical Journal, submitted (2016).
3. Wu, Y., Florinski, V., and Guo, X., Investigating pickup ions with New Horizons, Ulysses and Voyager, Astrophysical Journal, submitted (2016).